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THESIS

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TO
STUDY ATMOSPHERIC TRANSMISSION PROPERTIES

by

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The Construction of a Nd:YAG Laser
to
Study Atmospheric Transmission Properties

by

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ABSTRACT

A neodymium laser was constructed to be used in a study of atmospheric transmission properties of 1.06 micro-meter radiation. A Nd:YAG crystal was selected for use in the laser, and the physical and chemical properties of Nd:YAG as compiled from the literature are presented. A detailed description of the laser system design is given with the expected operational characteristics. The laser was operationally tested a number of times during which several of the design parameters were varied, but lasing action was never observed. An outline of the probable causes for failure is given in the concluding remarks.

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I. WHY STUDY ATMOSPHERIC TRANSMISSION PROPERTIES

In recent years the rapid advances made in laser technology have made laser communication systems a reality. The military community is particularly interested in these new systems for the enormous information capacities and line-of-sight security that are possible with such systems. Lasers are currently being used for target designation and high resolution rangefinders with extensive research being conducted in communications and the high energy laser as a primary weapon. Before any of these system designs can be optimized and their full capabilities realized, it is essential to know how changes in the atmosphere will affect their performance.

In the past only the microwave portion of the electromagnetic spectrum was utilized for communication and similar type systems. As a result the effects of the atmosphere on this type of radiation are quite well known. With the development of the laser the optical spectrum has become available for use, and it is necessary to determine the atmospheric transmission properties for this part of the spectrum. Very little has been done in this area to date, but it is receiving a great deal of attention by the military. The Navy has a particular interest in atmospheric effects in the presence of an ocean/air interface; thus far nearly the only research accomplished has been over land. The primary goal established is the prediction of electro-optic system performance as a function of the local weather conditions.

II. EXPERIMENTAL APPROACH

The general approach envisioned for this project is to set up a laser to propagate across a portion of Monterey Bay. The beam will then be analyzed at that location or a reflector could be set up to return the beam to the source point for analysis. The image will be analyzed using a special detector arrangement and the data will be correlated with meteorological information supplied by the meteorology department.

A neodymium laser was selected for this project for several reasons. The 1.06 μm radiation characteristic of neodymium is in the near infrared and lies in a very transparent portion of the atmosphere. Detectors for this wavelength are relatively simple and inexpensive. Also, neodymium lasers can be operated in the continuous wave mode at sufficiently high output powers to insure a meaningful range over which data can be taken. Since no continuous wave neodymium laser was available, it was decided that a Nd:YAG laser would be constructed. To date the total progress of the project has been the construction and the operational testing of this laser.

III. PROPERTIES OF ND:YAG CRYSTALS

Over the past several years a great deal of research has been accomplished in the development of solid state laser materials and systems. Among the most thoroughly studied have been neodymium lasers emitting radiation at 1.06 μm through a variety of host materials. The primary host materials studied have been glass and yttrium aluminum garnet (YAG). Although other crystalline materials have been tried as the host material, glass and YAG have certain characteristics which make them much better for high repetition rate, Q-switched laser systems.

A. ENERGY LEVELS OF TRIVALENT NEODYMIUM

Figure 1. is an energy level diagram of Nd^{3+} showing the laser transition between the two excited levels $^4F_{3/2}$ to $^4I_{11/2}$ which makes it a four-level system. The decay processes from the higher energy bands to the $^4F_{3/2}$ state are fast, non-radiative transitions. The $^4F_{3/2}$ state is metastable with a sufficiently long lifetime to allow population inversion to occur. The relaxation of the $^4I_{11/2}$ state to the ground state, $^4I_{9/2}$, is fast enough to allow the crystal to support continuous wave lasing action at room temperatures. This is the most important advantage of neodymium over ruby and other three-level systems where the lasing transition takes place to the ground state.

B. FLUORESCENCE PROPERTIES OF Nd:YAG

For design optimization of solid state laser systems it is important to know two particular properties of the crystal's fluorescence. They are, the fluorescence lifetime and the fluorescence conversion efficiency under optical exitation.

1. Fluorescence Conversion Efficiency

The 1.06 μm relative fluorescence conversion efficiency at 300°K as a function of excitation wavelength is presented in Figure 2.[1] This curve is temperature dependent in the temperature range 300-500°K. Although not shown in Figure 2., the peaks at .52 μm and .59 μm increase significantly with temperature and become dominant over those in the infrared at approximately 475°K. The peaks located in the infrared portion of the curve are essentially temperature independent.

2. Fluorescence Lifetime

The fluorescence decay of Nd:YAG from the $^4F_{3/2}$ energy level to the $^4I_{11/2}$ level is almost independent of temperature in the range 300-500°K. The average fluorescence lifetime as determined by Thornton, et al.,[2] in this temperature range was 228$\pm$15 μsec. The accepted value quoted in most other sources is around 240 μsec. The

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[1]J. Ronald Thornton, et al., "Properties of Neodymium Laser Materials," APPLIED OPTICS 8(June 1969): 1098

[2]Ibid., p. 1087

fluorescence lifetime is a strong function of the neodymium doping level and is presented in Figure 3.

C. PHYSICAL AND CHEMICAL PROPERTIES OF ND:YAG

Table 1. represents a summary of physical and chemical properties of Nd:YAG. Figures 4 and 5 are graphs showing some of the optical properties as functions of temperature. The values given in the table and the graphs were collected from various references cited in the bibliography.

TABLE 1.

Chemical Formula	$Y_3Al_5O_{12}$:Nd
Crystal Structure	
Symmetry	Cubic
Space Group	$O_h^{10}-I_a3d$
Lattice Constant	12.01 Angstroms
Melting Point	1970°C
Hardness	
MOHS Scale	8.5
Vickers (111)	1548
Specific Gravity	$4.56 \pm .04$
Water Absorption	zero
Solubility	
Water	Insoluble
Common Acids	Slightly
Thermal Expansion Coefficient (0-250°C)	
(100) Orientation	8.2×10^{-6} °C^{-1}
(110) Orientation	7.7×10^{-6}
(111) Orientation	7.8×10^{-6}
Thermal Conductivity	
20°C	0.0320 cal/sec-°C-cm
40°C	0.0290
100°C	0.0250
200°C	0.0225
Specific Heat Capacity (0-20°C)	0.140 cal/gm-°C
Modulus of Elasticity	0.45×10^6 lb/in^2
Tensile Strength	25-30×10^3 lb/in^2
Poisson Ratio	0.3 (est)
Refractive Index	$1.82 \pm .003$
Output Polarization	Unpolarized
Brewster's Angle	61.2°
Critical Angle	33.3°
Normal Dopant Level Nd^{3+}	0.7% by weight

IV. CONSTRUCTION OF THE LASER

The laser that was constructed is similar to a commercial laser produced by Raytheon Corp., Model LCW3Q, with a measured output power of 1-2 Watts in the cw mode and capable of being mechanically Q-switched for 200 nanosec pulses of 1 KW at a pulse repetition rate of 5 KHZ. Similar operating characteristics were expected for this laser. The Nd:YAG laser rod used had the following dimensions: it is cylindrical in shape with a diameter of 3 mm and length 75 mm. The ends are cut plane parallel with an anti-reflection coating for 1.06 μm. Two rods of identical specifications were purchased, one from Crystal Optics Research, Inc. and the other from the Airtron Division of Litton Industries. The completed laser system has three major subsystems comprised of; the optical pumping cavity, the pump cavity and laser rod cooling systems, and the optical resonator.

A. THE OPTICAL PUMPING CAVITY

The cavity geometry is a double-elliptical cylinder with the two ellipses having a common focus. The rod is aligned parallel to the cylindrical axis on the common focus. Figure 6. is a detailed drawing of the cavity. The cavity was machined from a solid block of aluminum by drilling off-set holes for each ellipse and hand finishing to the desired shape. It was then polished and the reflecting surface gold coated by the evaporation technique. The end plates (see

Figure 7.) were made from 5/16 inch aluminum plate with the surface towards the ellipses polished and gold coated.

Optical pumping of the rod is accomplished with two tungsten-iodide, quartz-envelope lamps placed at the other foci of the ellipses parallel to the rod. The lamps used are manufactured by General Electric, mfg. stock no. Q1000T3/4CL, with a rated output of 1000 watts at 120V. Figure 9. shows the details of the lamp mounting assembly.

B. OPTICAL PUMP CAVITY AND LASER ROD COOLING SYSTEMS

The original design called for a completely closed loop cooling system so that the laser would be totally portable. However, after several trials using ice bath and refrigerated heat exchangers, it was found that the pump cavity developed too much heat to be efficiently removed by these methods. The final design used is described in the following paragraphs.

The cavity is cooled by passing tap water through holes drilled in the cavity block. Multiple pass circulation was achieved by milling out channels between holes on alternate sides of the block and sealing them against leaks with rubber O-rings. Figure 6. gives the details of this arrangement and indicates water flow directions with arrows. This design proved quite efficient; when using tap water at 21°C with the lamps operating at maximum power the cavity feels slightly warm to the touch.

The laser rod is enclosed in a 9mm pyrex glass tube through which de-ionized water is circulated by a closed

loop cooling system. Figure 8. displays the details of the laser rod mounting and cooling assembly. Cooling of the de-ionized water inside the loop is achieved by using a simple copper heat exchanger utilizing the tap water enroute to the cavity. Figure 10. is a schematic diagram of the closed loop system. The pump used was an impeller type with a rated output capacity of 5GPM. With the regulating valve in the wide open position the flow rate through the rod was measured to be .33GPM. Using maximum lamp power with 21°C tap water passing through the heat exchanger and cavity, the reservoir temperature stabilized at approximately 23°C with a thermistor reading at the rod outlet of 31°C. Since the pump uses the water passing through it for cooling, it is assumed to add some heat to the system prior to the rod inlet. However, no temperature measuring device was installed at the rod inlet making it impossible to determine the exact thermal gradient along the length of the rod.

C. THE OPTICAL RESONATOR

The optical resonator consisted of two, one inch diameter mirrors, one flat and the other spherically curved with a radius of curvature of 1.5 meters. The flat mirror was dielectric coated on one side for 95% reflectance and coated on the other side for maximum transmission. The curved surface of the spherical mirror was coated for maximum reflection. These mirrors were purchased from Valpe Corp.,

and according to spectophotometer recordings supplied by the manufacturer the coatings are effective over a narrow bandwidth of about 100Å centered at 1.06 μm. The mirrors were mounted in two inch diameter laser mirror mounts using adapter rings. The mounts have orthogonal, micrometer adjustments with an angular resolution of 1 arc second. Longitudinal adjustment can be made by positioning of the adapter rings within the mount.

To minimize diffraction losses, the ideal laser resonator is the confocal mirror configuration. This consists of identical spherical mirrors separated by a distance equal to the radius of curvature. In addition, this arrangement is much easier to align than a flat mirror resonator. The angular adjustment accuracy is reduced from 1 arc second to .25 degrees.[3] To determine the optimum mirror spacing for a curved, flat mirror resonator, normally referred to as half-confocal, examine the radiation field distribution of a confocal system. For a confocal resonator the field intensity, perpendicular to the resonator axis, is concentrated near the axis and falls off smoothly away from the axis. In particular, theory shows that for the lowest mode ($TEM_{o,o}$) this lateral distribution is approximately Gaussian. The amplitude is proportional to[4]

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[3]Grant R. Fowles, Introduction to Modern Optics, p. 274, Holt, Rinehart, and Winston, Inc., 1968

[4]Ibid., p. 276

$$\exp\left[\frac{-2\pi\,\rho^2 d}{\lambda(d^2 + 4z^2)}\right]$$

Here ρ is the lateral distance from the axis, and z is the distance from the midpoint. The mirrors are located at $z=\pm 1/2d$. The amplitude drops by a factor of 1/e in a lateral distance equal to

$$\rho_s = \sqrt{\frac{\lambda(d^2 + 4z^2)}{2\pi d}}$$

This is called the spot size. At the center, z=0, the spot size is $\sqrt{\lambda d/2\pi}$, whereas at either mirror, $z=\pm 1/2d$, the spot size is $\sqrt{\lambda d/\pi}$.

Hence, for the half-confocal resonator the ideal location for the flat mirror is at exactly one-half the radius of curvature of the spherical mirror. To visualize this, place a flat mirror at the midpoint of a confocal resonator (half the radius of curvature); the effect is to optically fold one curved mirror into the other. Therefore the flat mirror receives the maximum intensity from the curved mirror, reducing diffraction losses and alignment problems. For the mirrors used this is equivalent to a resonator length of 75cm.

V. THE DETECTOR

There are several good, inexpensive detectors available for use with 1.06 μm radiation. The detector selected was a PIN-10 silicon photodiode for determining if lasing threshold was reached. The diode was reverse biased with a 22 1/2V battery and connected in series with a micro-ammeter of internal resistance 1960 ohms. Several different resistances were wired in parallel with the ammeter and a selector provided so that different sensitivity ranges were available. The circuit diagram for the detector is given by Figure 11. The relative sensitivity of a PIN-10 diode to 1.06 μm radiation is approximately 20%. Considering the power levels expected from the laser, no difficulties were expected in detection of lasing action.

VI. ASSEMBLY OF THE LASER

The mirror mounts and laser cavity were mounted to an optical bench consisting of 4 inch aluminum channel stock 5 1/2 feet in length. The cavity and mirrors were mounted such that the rod and mirror centers would be colinear. The mirrors were originally spaced 75cm apart with the cavity 10cm from the flat mirror. This was considered optimum as previously discussed. However, this rather long cavity was too difficult to align properly and the spacing was eventually reduced to 30cm.

The resonator was aligned using both a He-Ne laser and a Norad auto-collimator. A mounting assembly was constructed that would accept either apparatus and adjustable in any direction to facilitate alignment with the rod axis. Once the laser or auto-collimator was aligned with the rod axis the mirrors were lined up by superimposing their respective reflections on a common point.

The optical bench was mounted on a simple dolly with foam rubber pads between the bench and dolly to minimize vibrational effects. The cooling system for the rod was connected using 3/8 inch plastic tubing. Rubber tubing was used to deliver tap water to the heat exchanger and cavity from a sink in the laboratory.

The lamps were wired in parallel through an ammeter to a General Radio Variac, Type Q-100, with a maximum power rating of 2000 watts, at 18 amps and 115V. Power was supplied to the Variac from a conventional wall receptacle located in the laboratory.

VII. OPERATION OF THE LASER

The first series of tests was run with the resonator spacing set at 75cm. The resonator was aligned using the He-Ne laser. Power to the lamps was set at maximum and the current and voltage were measured to be 17.7 amps and 125V respectively. With the detector at maximum sensitivity placed aligned with the rod axis, no lasing was observed. After readjusting the mirrors several times without success, it was decided that the auto-collimator might offer an improvement in alignment. Several attempts were made, but the length of the cavity created too many uncertainties and proper alignment was questionable. Here the decision was made to decrease the resonator length to 30cm.

With the resonator set at 30cm the second series of tests were begun. The resonator was easily aligned with the auto-collimator, but again no lasing action was observed. A filter was placed in front of the detector to remove the visible light so that the shunt resistance could be taken out of the circuit. This improved the sensitivity, but the results were still negative. At this point it was felt that we might be operating with the rod at too low a temperature. The temperature of the reservoir was then varied up to 40°C by using warmer water to the heat exchanger. When this failed to provide positive results, it was concluded that the lamp power must be too low to provide sufficient optical excitation for lasing threshold to be reached. To increase this power a

second Variac was obtained and the lamps were connected independent of each other. With this new arrangement power was increased about 10%. Readings taken on each lamp at full power indicated a total increase of approximately 260 watts; with a total power input of 2420 watts. Again, no success! Due to time limitations further testing was suspended.

VIII. CONCLUSIONS

Although the laser did not function properly the basic design is considered sound. The reduction in the length of the resonator undoubtedly introduced some small losses, however, alignment errors result in losses of much greater magnitude. With the shorter resonator alignment was considered certain, and resonator losses were assumed negligible. If this is the case, the only other problem that could be associated with the resonator would be a transmitting mirror with too little reflectivity. Nd:YAG lasers with similar characteristics described in the literature quote 95-98% reflectivity as optimum.[5] The resonator does not appear to be the problem.

The next item to be considered is the rod itself. Nd:YAG crystals are known to vary in quality from one manufacturer to the next and even from the same one. This could definitely be the primary cause for failure. Only the time limitation prevented the spare rod from being tested, and it is recommended that if tests are conducted in the future the rods be interchanged.

Assuming that the rod was good, the cause of failure must be considered to be insufficient or improper optical

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[5] I. Liberman and R. L. Grassel, "A Comparison of Lamps for Use in High Continuous Power Nd:YAG Laser," Appl. Optics, v. 8, p. 1877, September 1969.

excitation of the rod. If the case is insufficient excitation it must be a problem with the optical pumping arrangement. It is surely linked to the efficiency of the pump cavity. An attempt will now be made to estimate the efficiency of the cavity that is acceptable.

First calculate the minimum gain of the laser rod necessary to sustain lasing action. It can be shown[6] that the intensity in a laser rod grows as

$$I = I_o \, e^{a_f x}$$

where a_f is the gain of the medium and x is the distance traveled through the medium. For an optical resonator, lasing threshold is reached when the gain in the laser rod just cancels the losses of the resonator and the medium. If the laser rod is of length L then for one oscillation

$$I = I_o \, e^{a_f 2L}$$

The resonator losses must now be estimated. There is a built in loss of 5% at the transmitting mirror, and assume another 10% loss is associated with mirror absorption, diffraction losses, and rod imprefections. Solving for a_f we obtain

$$a_f = \frac{\ln(I_o/(.9)(.95)I_o)}{(2)(7.5)} \quad (\mathrm{cm}^{-1}) = 0.01 \ \mathrm{cm}^{-1}$$

[6]Ibid., p. 270

The next step is to determine the minimum power required to sustain laser threshold. To do this, look at the population inversion required. This can be written in the form[7]

$$n \cong \frac{a_f 8\pi c}{\lambda^3 A_{21}} \; \frac{\Delta f}{f}$$

Where n is the excess number of atoms per unit volume in the metastable state, $\Delta f/f$ is the fractional linewidth of the laser transition, and λ the transition wavelength. A_{21} is the Einstein coefficient of spontaneous emission and is equal to the reciprocal of the metastable state lifetime (for Nd^{3+} $\cong$ 230 μsec). Hence, the minimum power required to sustain laser threshold in a rod of volume V, can be written as[8]

$$P_{min} = \frac{nV(hf)}{\tau} = \frac{a_f 8\pi c V(hf)}{\lambda^3} \; \frac{\Delta f}{f}$$

where hf is the energy of the metastable state. Using the properties of Nd:YAG previously given and assuming that all excitation photons have energy 1.3eV (the energy of the $^4F_{3/2}$ state), then P_{min} for the laser rod used is

$$P_{min} \cong 0.4 \text{ watt}$$

However, the coupling of the optical light to the rod is certainly not 100% efficient, and the average energy of an

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[7]Ibid., p. 267

[8]A. L. Schawlow and C. J. Townes, "Infrared and Optical Masers," Physical Review, v. 112, p. 1942, December 1958

excitation photon from a tungsten lamp is greater then 1.3eV. Assume these losses raise P_{min} by a factor of 2, then 0.8 watt is required to sustain threshold.

To finish the calculation find the power that would be available to the rod using a 100% efficient cavity when operating the lamps with 2000 watts electrical power. Tungsten lamps convert electrical power to optical power with an efficiency of 90%, but only 30% of this energy is at wavelengths shorter than 1μm.[9] Also, a typical Nd:YAG rod can only absorb 1/10 of this energy due to its narrow absorption bands. This means, that of the 2000 watts electrical power input to the lamps, only 54 watts of optical power is available for absorption if all of it is imaged on the rod. Hence, the minimum efficiency of the cavity used, E_{min}, to sustain threshold would be

$$E_{min} = (o.8/54)100\% = 1.5\%$$

On the surface this appears quite reasonable and should be easily attainable. However, at least two of the assumptions made in calculating E_{min} are dependent on the laser itself and may be in considerable error.

The coupling of optical power to the rod may be considerably less than supposed. The glass tube surrounding the laser rod may have a high reflection coefficient for the pumping wavelengths; thus, the factor of 2 used in the computation

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[9] Z. J. Kiss and R. J. Pressley, "Crystalline Solid State Lasers," Applied Optics, v. 5, p. 1480, October 1966.

may be significantly higher and this is directly proportional to E_{min}. Also, the internal losses of the rod could be much greater than assumed. Recall that the water flow rate through the rod cooling system was .33GPM; the instruction manual for the Raytheon laser specifies a flow rate of 1.5GPM. This slower flow rate could lead to thermal gradients which could result in thermal defocussing. If this happens, and losses in the rod are much higher than assumed, a_f will be increased and E_{min} will also increase.

It is extremely difficult to estimate the true efficiency of the laser cavity that was used. For well designed single-ellipse geometries, efficiencies of greater than 50% have been realized. A perfect double-elliptical cavity is inherently less efficient, and the cavity used was far from perfect. The method used to shape the ellipses was very crude, and the evaporation of gold on to the reflective surface is undoubtedly inferior to one electroplated with gold.

The laser might be made operable by simply changing the laser rod as previously mentioned. If this fails, it appears that the pumping cavity will have to be made more efficient.

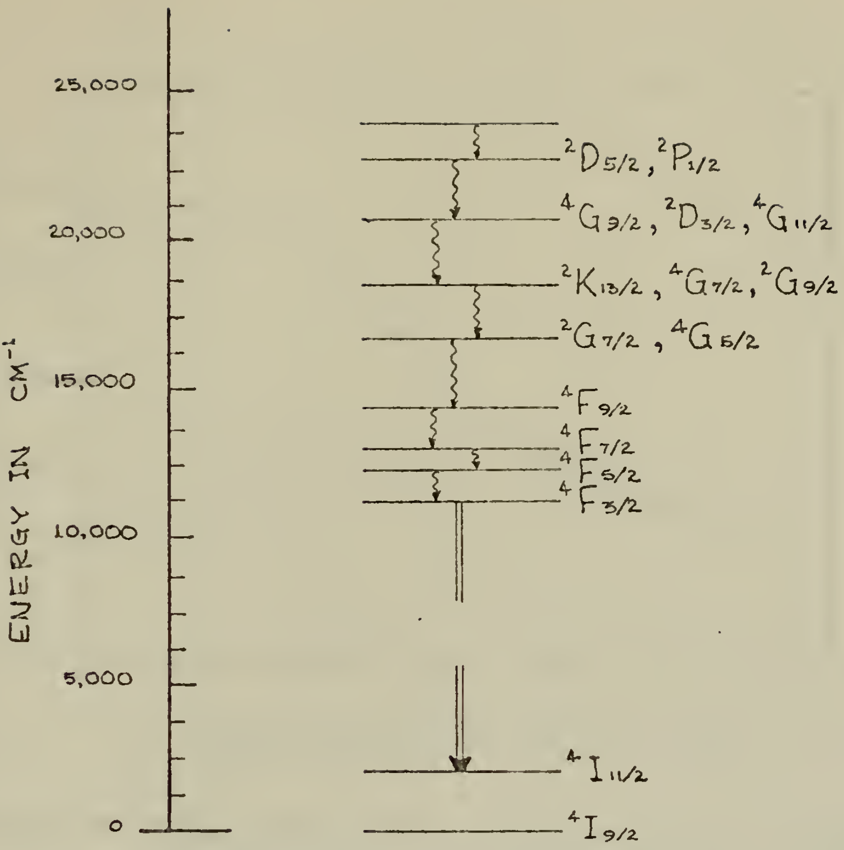


Figure 1. Energy Level Diagram of Trivalent Neodymium

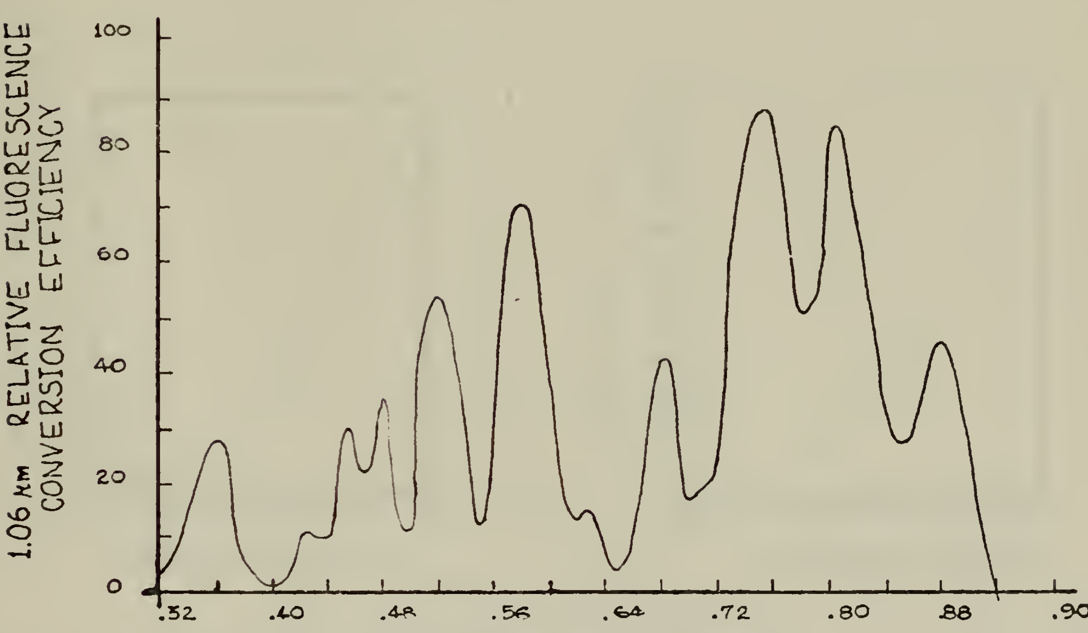


Figure 2. Relative Fluorescence Conversion Efficiency of Nd:YAG at 300°K

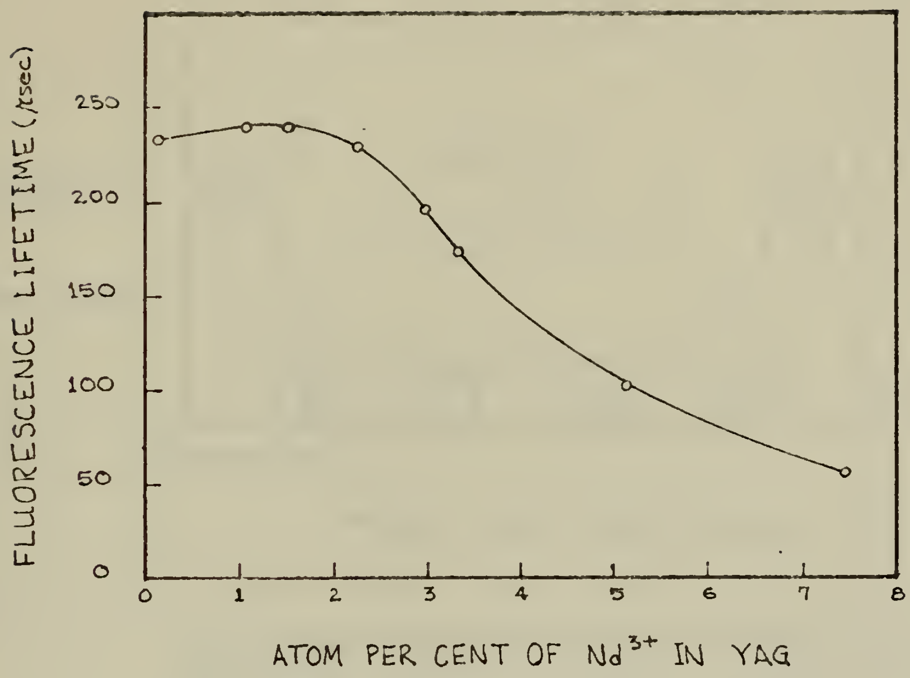


Figure 3. The Lifetime Dependence of the 1.06 μm Fluorescent Line in Nd:YAG with Nd^{3+} Concentration

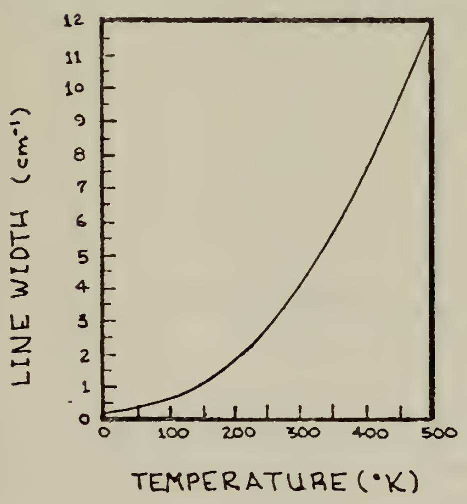


Figure 4. Linewidth of Nd:YAG 1.06 μm Fluorescent Line with Temperature

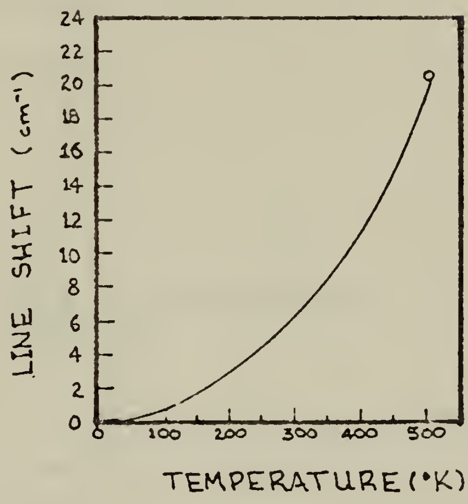
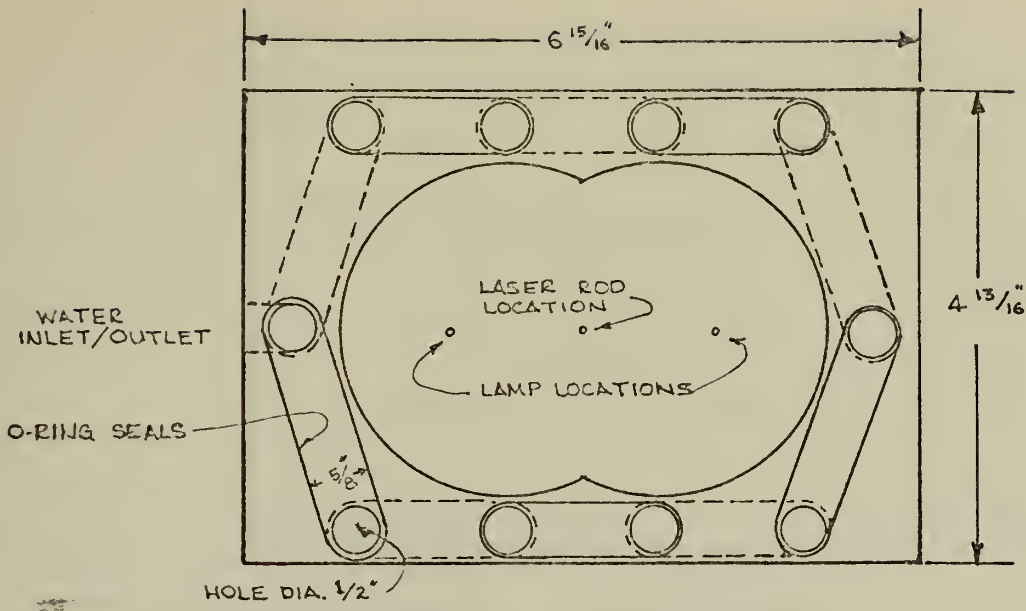
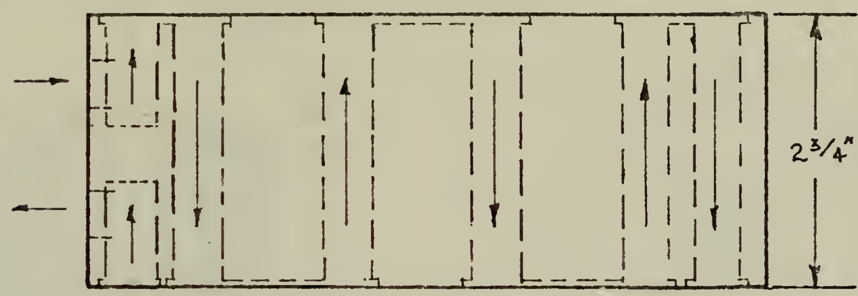


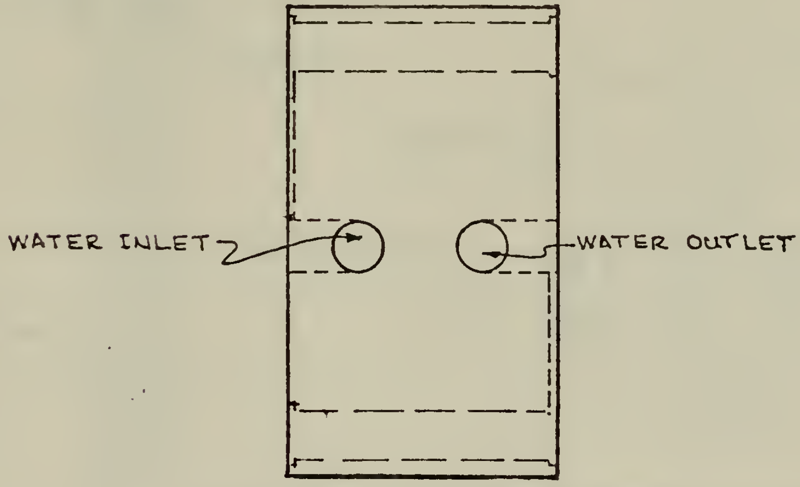
Figure 5. Line Shift of a Nd:YAG 1.06 μm Fluorescent Line with Temperature



OPTICAL AXIS VIEW SCALE: 1" = 1/2"

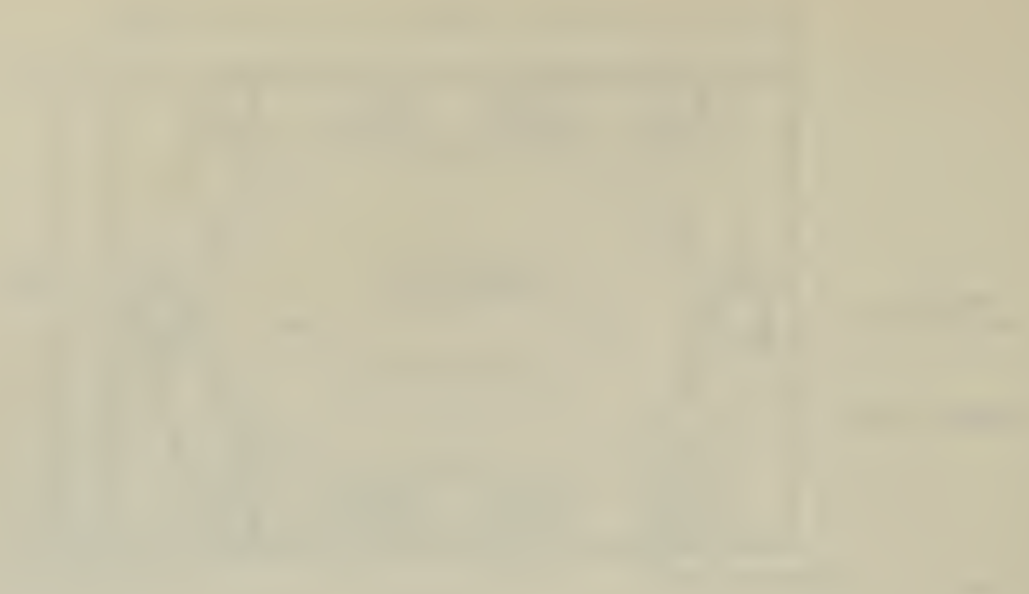


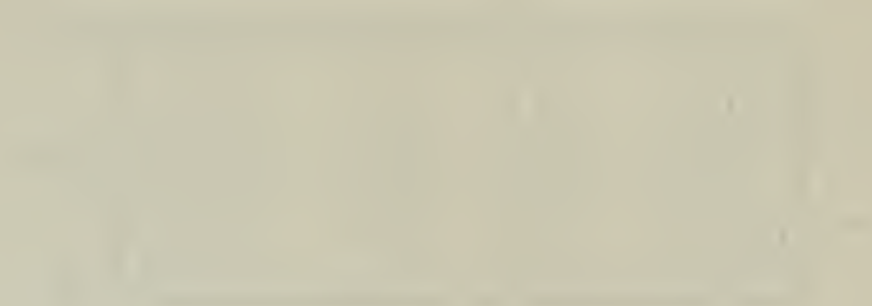
TOP VIEW SCALE: 1" = 1/2"



END VIEW SCALE 1" = 1/2"

Figure 6. Optical Pumping Cavity





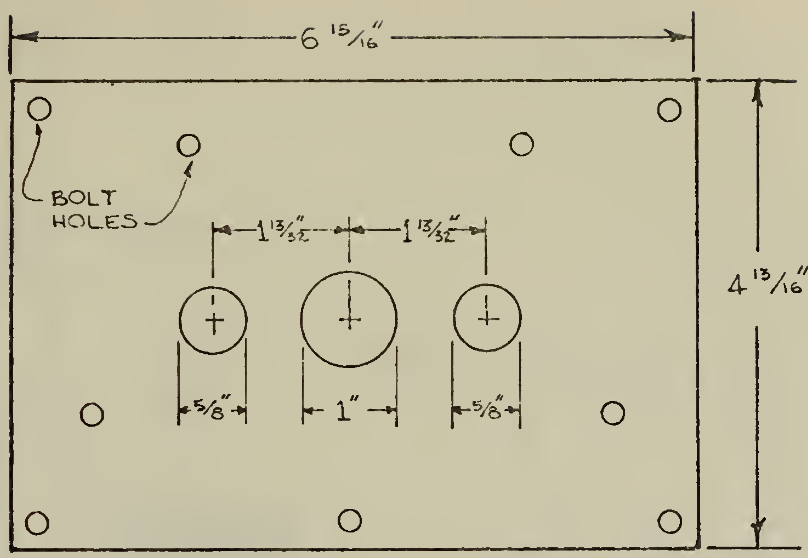


Figure 7. End Plate Scale 1"=1/2"

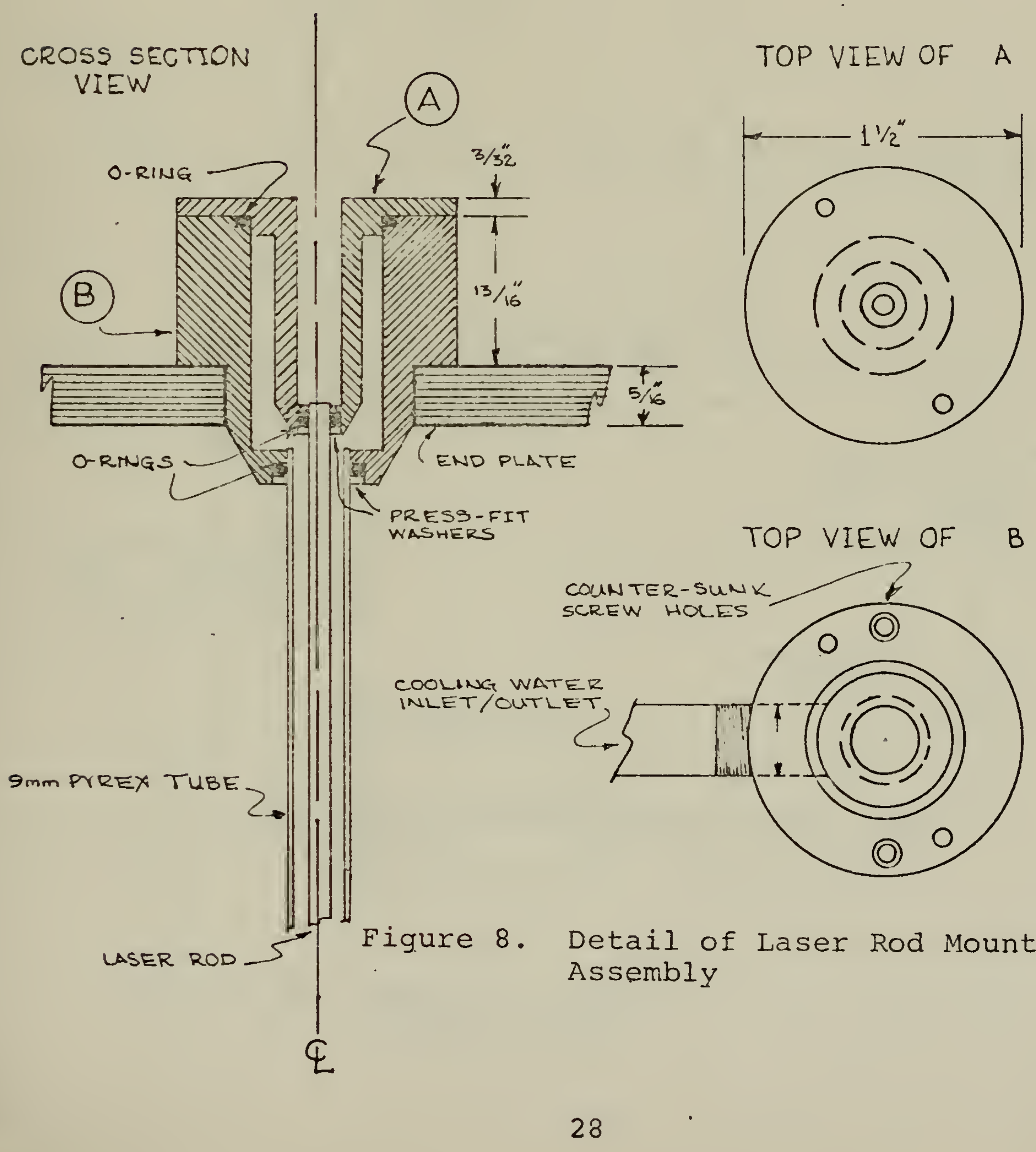


Figure 8. Detail of Laser Rod Mounting Assembly

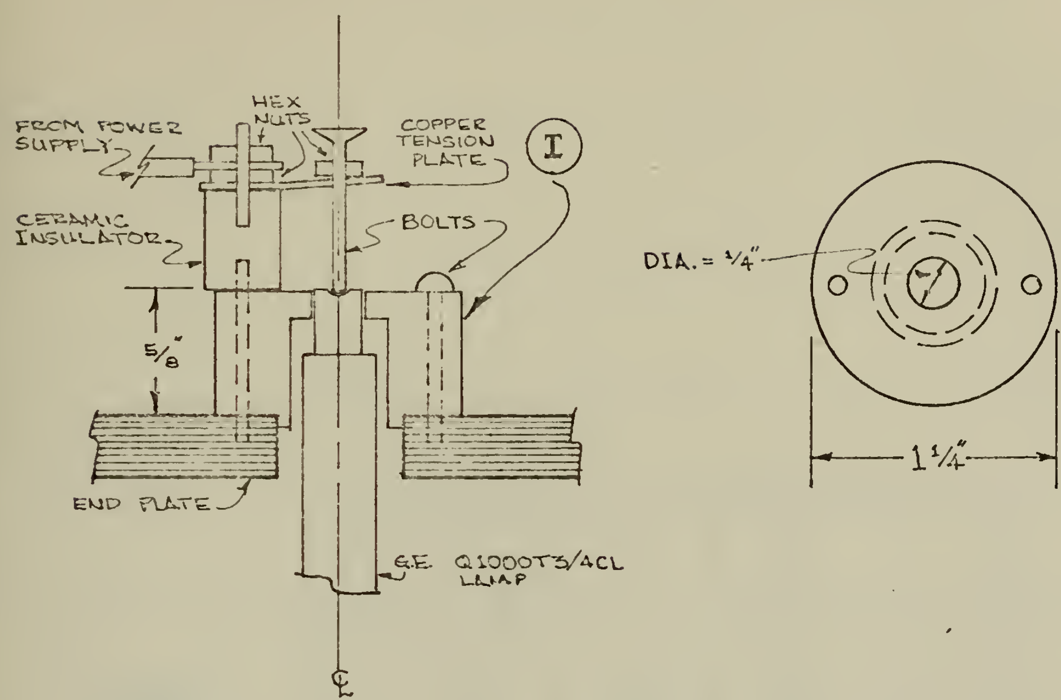


Figure 9. Detail of Pump Lamp Holding Assembly

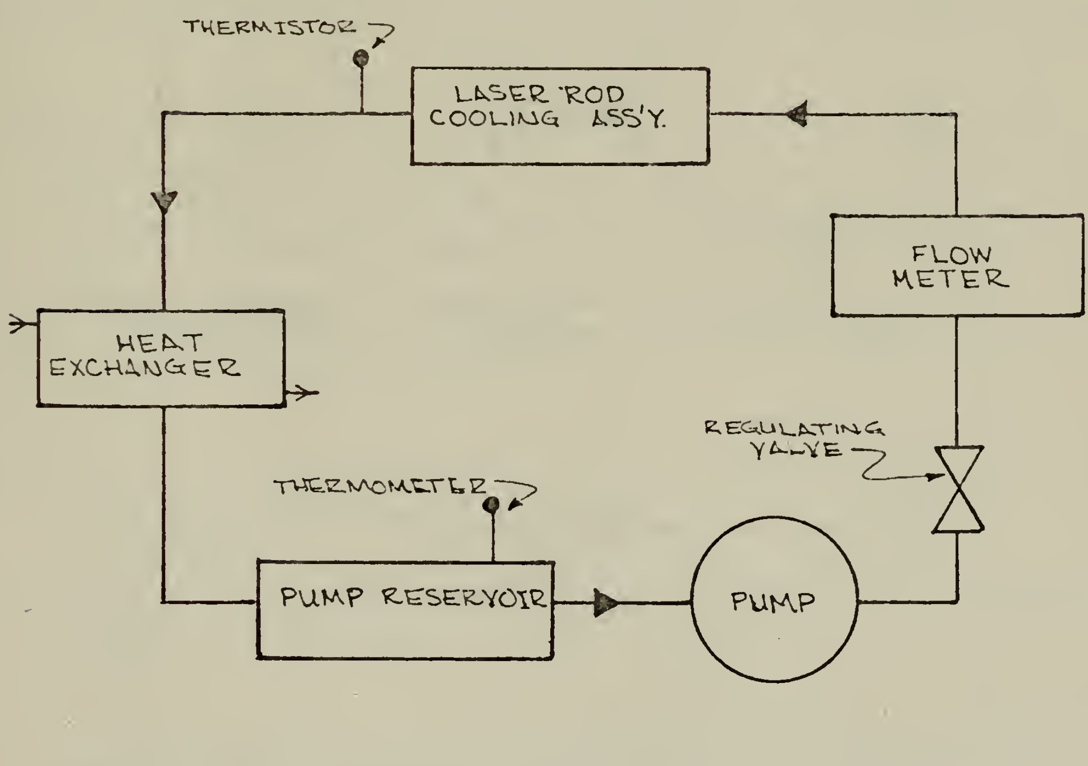


Figure 10. Schematic Diagram of the Laser Rod Cooling System

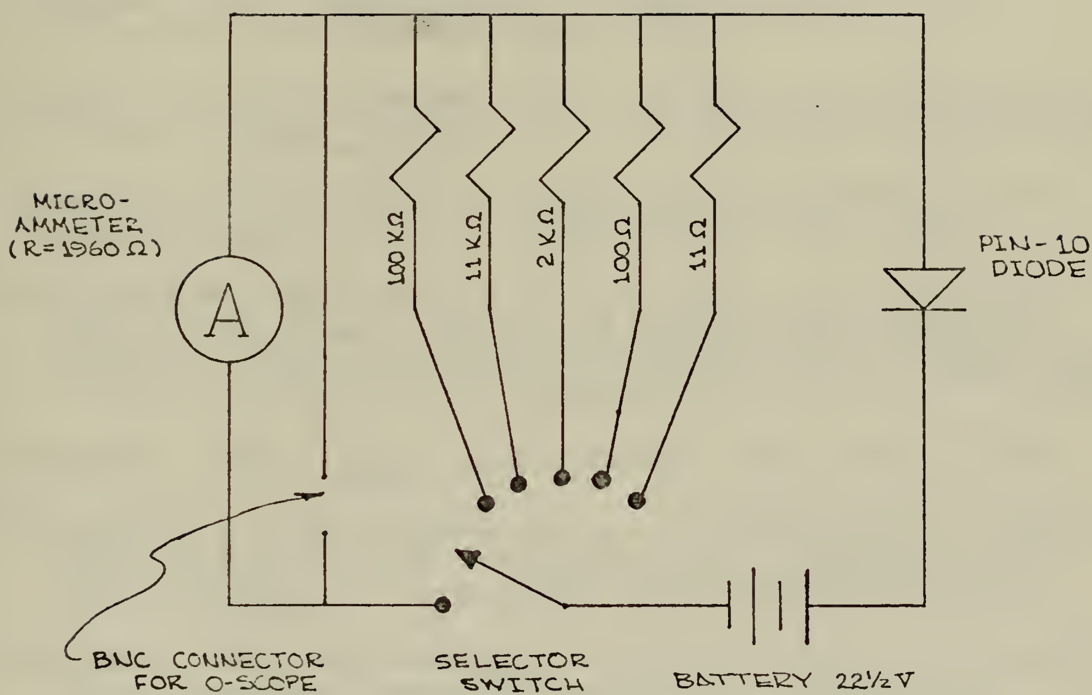


Figure 11. Circuit Diagram for Detector

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ABSTRACT

A neodymium laser was constructed to be used in a study of atmospheric transmission properties of 1.06 micro-meter radiation. A Nd:YAG crystal was selected for use in the laser, and the physical and chemical properties of Nd:YAG as compiled from the literature are presented. A detailed description of the laser system design is given with the expected operational characteristics. The laser was operationally tested a number of times during which several of the design parameters were varied, but lasing action was never observed. An outline of the probable causes for failure is given in the concluding remarks.

KEY WORDS	LINK A		LINK B		LINK C	
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